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Case study of non-linear PV inverter devices attached to the LV distribution network

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Abstract. Every year, more and more solar power plants are connected to the grid, producing electricity in an environmentally sustainable manner. The increasing number of photovoltaic (PV) installations and their integration into the low voltage (LV) distribution network (DN) is having an impact in terms of power quality (PQ). For example, the voltage in the DN can sustain high distortion values. The impact of a PV installation on the LV network is analysed in this research. The field measurements were carried out over a 3-week period at a solar power plant with a total output power of 160 kW in an Estonian rural municipality. The measurement results provide the opportunity to look more closely at the effect of the solar power plant on the supply voltage of the LV DN. Parameters such as voltage variation within a one-minute period, the asymmetry of the voltages and the total harmonic distortion of the voltages are discussed here.

Key words: distribution network, microgeneration, photovoltaic systems, power quality, solar energy, voltage level, voltage quality.

INTRODUCTION

The share of Renewable Energy Resource (RES) in the grid is increasing day by day. It will continue to grow more in the coming decades as most of the countries have plans for generating energy from 100% RES (Tan et al., 2017; Chen & Liu, 2019; Gürtürk, 2019; Hassan et al., 2019). Most of the RES electric producers including the photovoltaic (PV) installation units are directly dependent on environmental or atmospheric conditions (Shabbir et al., 2020) and their energy generation is not smooth rather variable or stochastic in nature (Demolli et al., 2019; Shabbir et al., 2019). Therefore, the usage of RES in such high capacity requires more technical but elaborative solutions. This may cause serious power quality (PQ), reliability and flexibility issues in the grid. For example, the network voltage levels can drop significantly while increased values of harmonic distortions are seen (Ruwaida & Holmberg, 2015). This can be caused by even a single small scale PV producer integrated directly to low voltage (LV) distribution network (DN) power line (Vinnal et al., 2018). Therefore, a large number of similar installations could have a very severe and adverse impact on the grid leading to equipment malfunctioning on the consumer side.

The general operating requirements of an LV distribution network in European DNs are defined within standard EN 50160. As per the standard, the RMS voltage V_n has to remain between ± 10% of the rated voltage during 95% time in a week (Seme et al., 2017). The limits of voltage harmonics tolerable are additionally defined in IEC 61000-2-2 (Meyer & Kilter, 2014). In case these limits are exceeded, the consumer device can sustain damage due to overheating or malfunction. The origins of voltage harmonics in the DN can be traced to current harmonics non-linear devices such as variable speed drives (VFDs), power electronics equipment and an increasing number of solar photovoltaic (PV) and wind RES (Iqbal et al., 2018).

These distortion components are also termed, as harmonic components are usually not significant, compared to the mains frequency voltage component values. Therefore, for the majority of the time, they do not cause equipment loss of function nor failure. Nevertheless, the level of voltage harmonics directly affects the supply voltage quality, capacitors lifetime and power losses in motors and transformers.

The general requirements for connecting a small solar PV to the LV network list frequency and voltage synchronization, and ranges for power factor and voltage unbalance values. The power of a small PV plant is of variable nature, having a diverse effect on these parameters at different times. In extreme cases, the parallel operation of the LV network and PV plant can cause disruptions in the reliable operation of the network. On the other hand, the presence of a PV plant in the distribution can sometimes attribute to the reduction of the harmonics of the phase voltage as compared to the case without having a PV plant. A further drop in total harmonic distortion (THD) values is possible by using switching and semiconductor converters with power factor correction (PFC) (Kopicka et al., 2014).

A high number of papers have been made available on the effects of PQ in the LV distribution network due to the presence of small PV units in the grid. In (Urbanetz et al., 2012) Studied on the effects of the PV generator attached to the LV network found that PV integration in the LV network is beneficial for improving PQ indexes like harmonics and THD. Similarly, the effect of a large PV unit of 1.8 MW connected to the grid is discussed in (Farhoodnea et al., 2012). The presence of such a high power source caused a rise in voltage and flickering and loss in power factor. The harmonic currents and the voltages in LV distribution networks have been elaborated in (Vinnal et al., 2018). A case study on the impact on power quality has been discussed for different PV generators connected to the grid in (Kumary et al., 2014). In (González et al., 2014), PQ parameter measurements at different points in the LV distribution networks showed that the power factor would decrease, voltage and current harmonics remained low but the problems were associated with fluctuations in frequency and increased voltage levels. The problems related to voltage variations and flickering are discussed more in (Pakonen et al., 2016). The evaluation of harmonic distortions associated with PV units is described in (Shi, 2014; Grasso et al., 2018). An integration model of solar PV into the grid has been developed in DigSilent (Jayasekara & Wolfs, 2010), for the analysis of PQ parameters. Studies listed above indicate the significance of PV plants to the PQ indexes and grid operation.

The main focus of this article is to present and analyse selected PQ aspects related to small-scale PV integration in the LV network with particular site case analysis in Estonia. The parameters discussed here are voltage magnitude, fluctuation and harmonics.

The organization of this paper is as follows: section II describes the analysis of PV and LV distribution systems in Estonia along with a description of the measuring site and measurement equipment. The results and discussions are presented in section III. Finally, section IV presents the conclusion and recommendations of this study.

ANALYSIS OF DISTRIBUTION SYSTEM

A. Description of the PV System and LV Network

The measurements were made at a power plant located in Harju County in Estonia. The construction of the power plant began in October 2015 and was completed in one year. An initial payback period of 10 years was estimated for the construction of the plant.

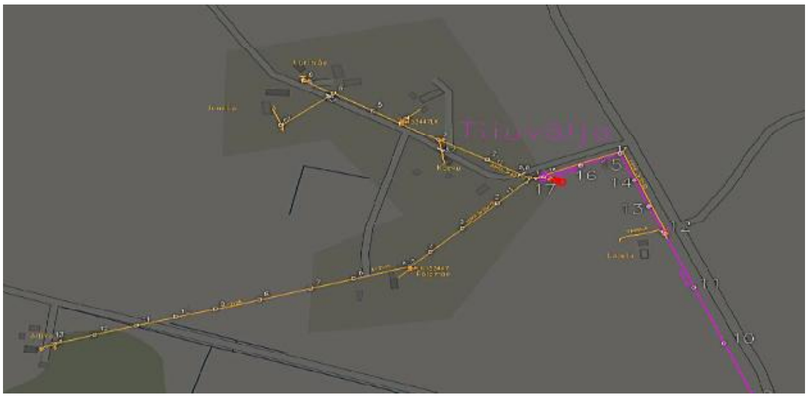

Figure 1. The low-voltage electric network of the considered solar power plant.

This solar power plant is connected to the LV terminals of the 10 / 0.4 kV substation. Fig. 1 shows a map of the low voltage circuit surrounding the substation. The purple colour represents the 10 kV high voltage power line of the substation. The PV panels are shown in Fig. 2 while Fig. 3 shows the transformer along with the LV distribution line.

Figure 2. The PV panels and inverters installation.

Figure 3. Solar Power Plant point of common coupling (PCC) with a 10 / 0.4 kV substation in the background.

The solar plant includes 668 solar panels with a total output of 177 kW. The total power of the inverters is 160 kVA. There are six inverters - two at 20 kVA and four at 30 kVA.

The entire power plant is divided into six production units by means of six inverters, all of which are concentrated in one main switchboard with circuit breakers. The main switchboard collects all the energy produced and transmits it to a single cable power grid. Separation of inverters into separate production units has created a situation where, for example, if something should happen to one inverter or other devices, 5/6 of the station can continue to run uninterrupted.

B. Instruments and Measurement Procedure

The measurements at the PV station were conducted from September, 2nd until September 25th, 2018 using a three-phase PQ analysed device capable of recording voltage, current, active and reactive power, frequency, voltage asymmetry, as well as the proportion of harmonics of voltage and current up to the 50th harmonic.

Fig. 4 shows the main switchboard and measuring device with four wires for measuring voltage and Rogowski sensors for measuring current. The measurement period for long-term measurements was three weeks and the records over this time at one-minute intervals over the network. The following subchapters present a selection of the data stored by the meter and analysed it.

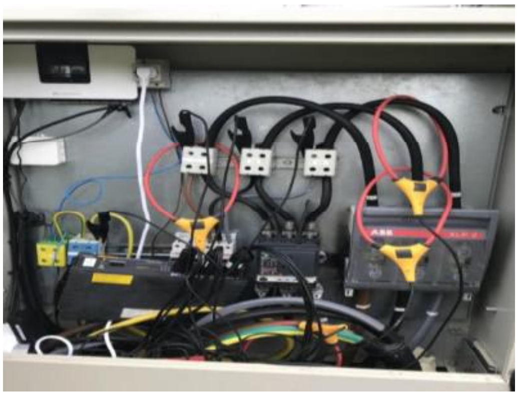

Figure 4. Main switchboard and PQ measurements.

MEASUREMENT RESULTS ANALYSIS

A. Power output ratings

The total power of the inverters of this station is 160 kW and the calculated average power output of the first week was 56.0 kW, in the second week 47.4 kW and in the third week 49.7 kW. Fig. 5 shows the output power of PV panels for the first week. Productivity was steadily high with the weather being rather clear. As only September 15th was low in productivity, the period of measurement can be considered successful.

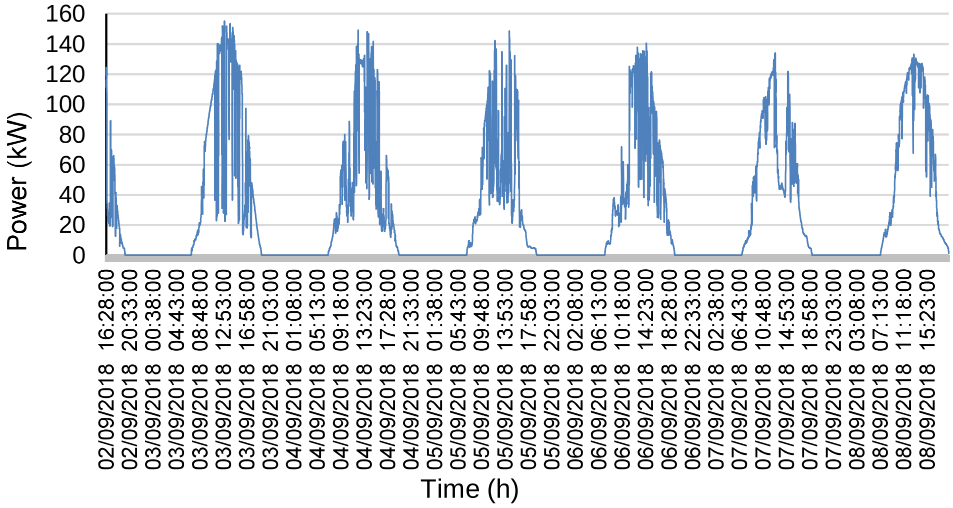

Figure 5. PV plant output power during the first week.

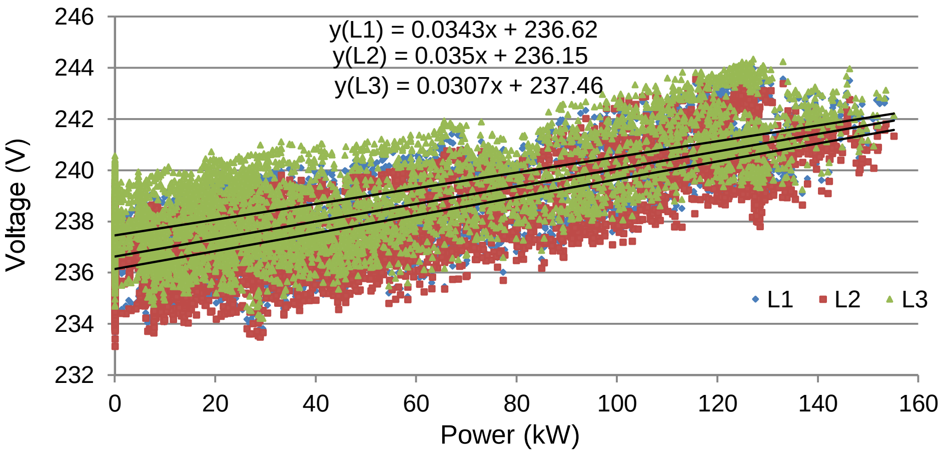

Figure 6. The output voltage of the solar panels, with trend lines corresponding to each of the three LV supply network phases.

Fig. 5 shows that solar power generation is highly cloudiness-dependent and incidental. Fig. 6 shows the weekly voltage dependence of the output voltage. From the graph, it can be seen that as the output of the solar power plant increases, the mains voltage increases. The graphs also present linear trend lines constructed by measuring points, by phase. Trend line equations are written at the legend and their increments over three weeks range from 0.029 P_{out} to 0.039 P_{out}, where P_{out} is the corresponding power output in kW. It can be seen that on average, the voltage rises between 4.6 V and 6.3 V at 160 kW power output.

B. Voltage level and symmetry

The difference between the maximum and minimum voltage values as a function of productivity is shown in Fig. 7. In addition to the average of one minute, the measuring device also recorded the maximum and minimum values of voltages during the same minute. Although the trend lines in the figures are ascending, they are small. Thus, it can be argued that the operation of this solar power plant does not influence the voltage fluctuation for a period of one minute.

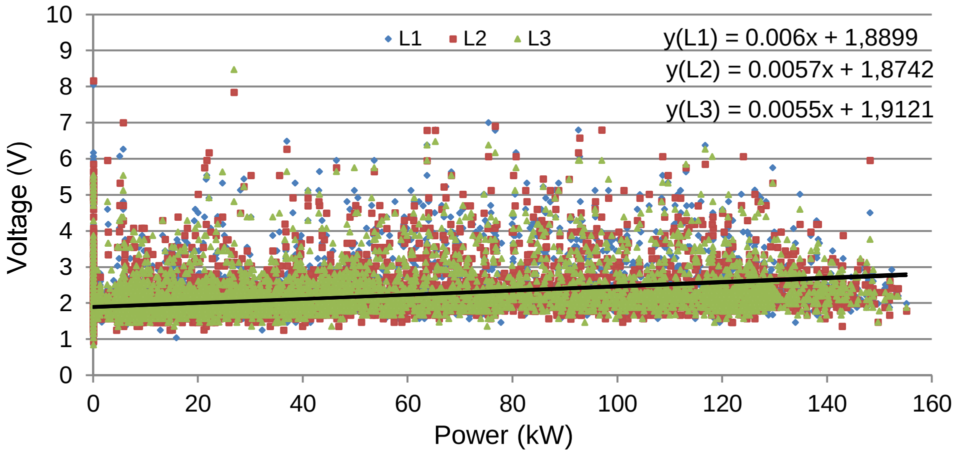

Figure 7. Difference between the minimum and maximum voltages in the LV network.

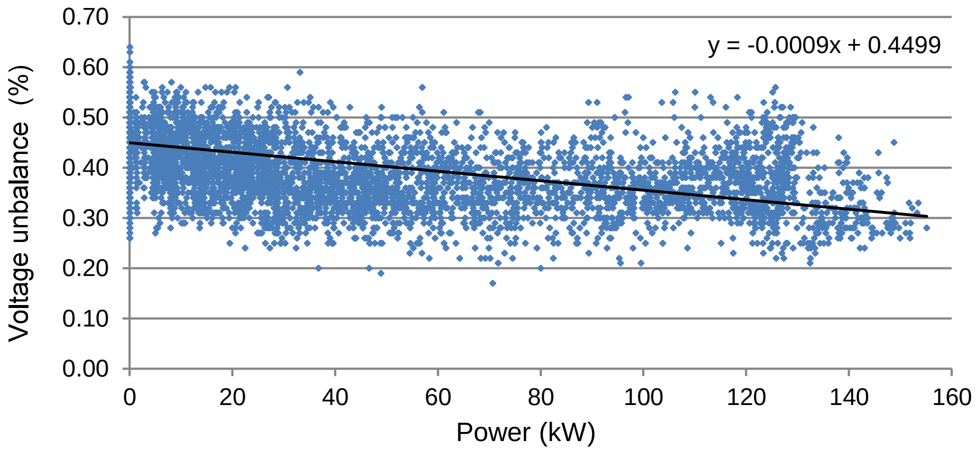

Figure 8. Voltage asymmetry as a function of output power during the first week, also with a trendline describing the relation to PV plant output power.

Fig. 8 shows the dependence of the voltage asymmetry on the output of the solar power plant. It shows visually that the points are horizontal rather than ascending or descending, although the trend line is descending. A decrease in asymmetry with productivity increases can be observed in the arrangement of the measuring points. In the first and third weeks, the average productivity was also higher than in the second week.

C. Voltage distortions

The dependence of the total harmonic distortion on the output power is shown in Fig. 9. The three-week trend line increases are in the range 0.0009 P_{out} to 0.0028 P_{out}, where P_{out} is the corresponding power output in kW. If P_{out} is replaced by the total power of the inverters, the harmonic total distortion of the voltages will increase, on average, between 0.14% and 0.45% at maximum output.

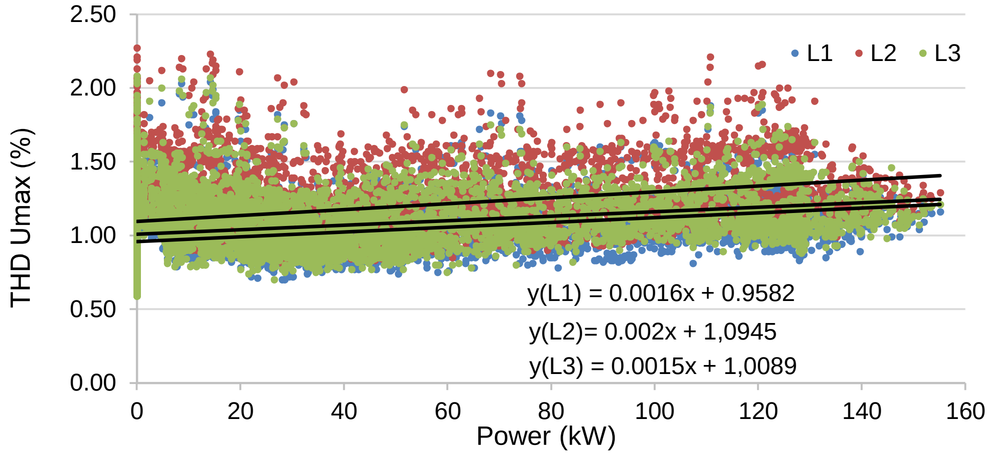

Figure 9. Voltage THD on the output of the solar power plant during the first week, plot based on output power.

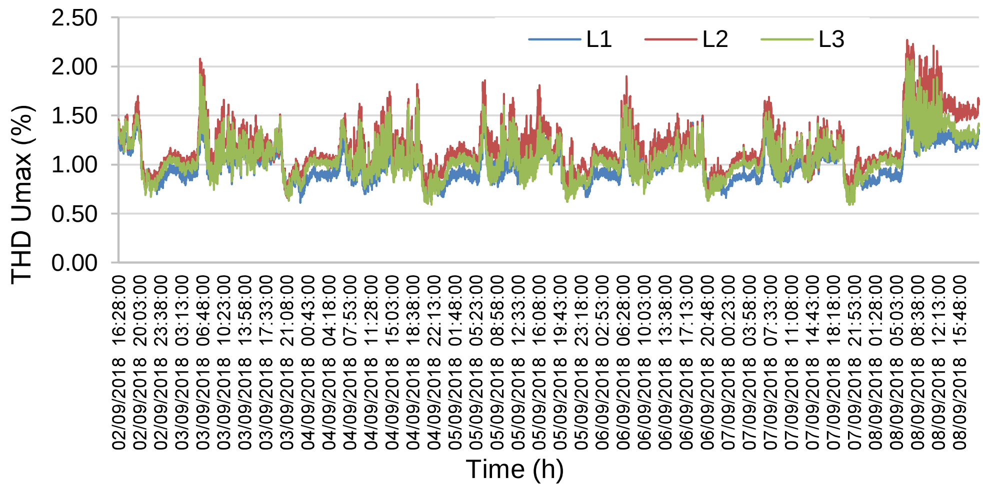

Figure 10. Voltage THD during the first week of measurement, detailed time plot.

Fig. 10 shows the total harmonic distortion of the voltage over three weeks' time. It can be seen from the figure that the level of total harmonic distortion during the night period is much lower than during the daytime. One reason for this may be the operation of the inverters of the solar power plant, but also the fact that consumers in the grid use more devices during the day, which can cause harmonic distortions in the grid.

D. Power output transients

An additional set of measurements were carried out at the PV plant with experimental shutdowns of the power plant. The most effective way to perform the shut-down was to through the use of the main switchboard, which can be seen in Fig. 11. Measurements were made with a PQ analyser unit, which provided recordings with a 1-sec sections of data for every two minutes.

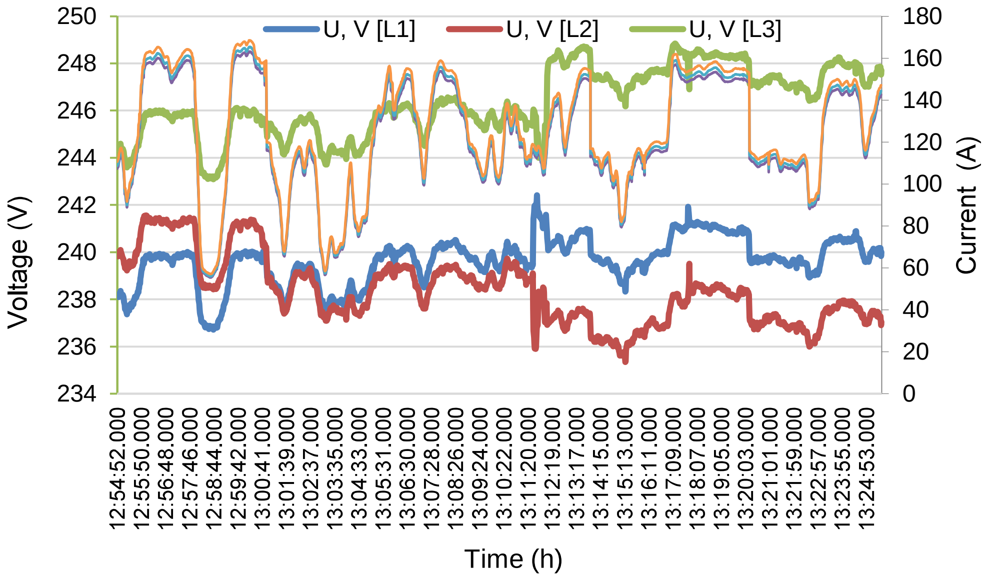

Figure 11. Switching off 2x20 kVA inverters for short periods.

On the main switchboard, two lines from the 20 kVA inverters were connected to one circuit breaker and four lines from the 30 kVA inverter units were connected to the second circuit breaker. Fig. 11 shows the voltage and current measurement data recorded during the shutdown period of the smaller production units. The graph shows that the sharp drop in production also has an immediate effect on the voltage level. As the two smaller inverters together make up only 25% of the total station output rating, it is not possible to clearly distinguish from the graph the moment when the clouds covered the sun for the station.

Fig. 12 shows a section of a period of voltage and current sine waveform. It can be seen in both figures that there is no significant distortion of the sinusoidal current and voltage in the phases. The voltage sine waveform is smoother than the current waveform, but the difference is rather small. The PEN conductor current in Fig. 12 reveals that high-frequency content with a magnitude close to 1 A is present. It can also be seen from

Fig. 12 that the PEN conductor current is in the same phase as the L1 phase current, i.e., when the L1 phase current is at its peak, the PEN conductor current is at its peak value.

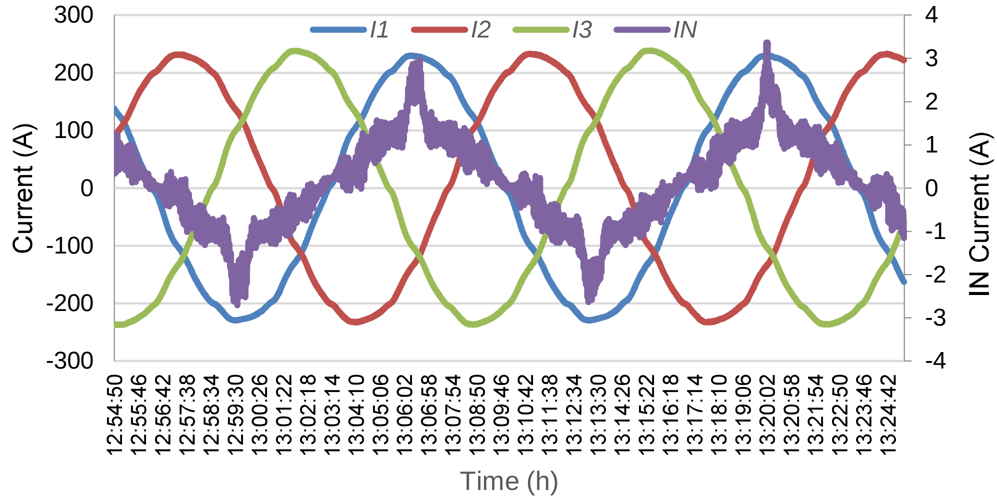

Figure 12. The current shape of three phases and PEN conductor for one period at a high output power.

Fig. 13 presents voltages and currents recorded during the whole station shutdown tests. The first shutdown was at 13:27, the second at 13:33 and the third was at 13:40. From 13:40 to 13:52 the solar power plant was kept isolated from the grid. At the same time, all six inverters were manually switched to idle mode and, at 13:52, the solar power inverters were connected to the mains in idle mode. Starting at 14:08 the inverters began operating in sequence to restore power to the grid.

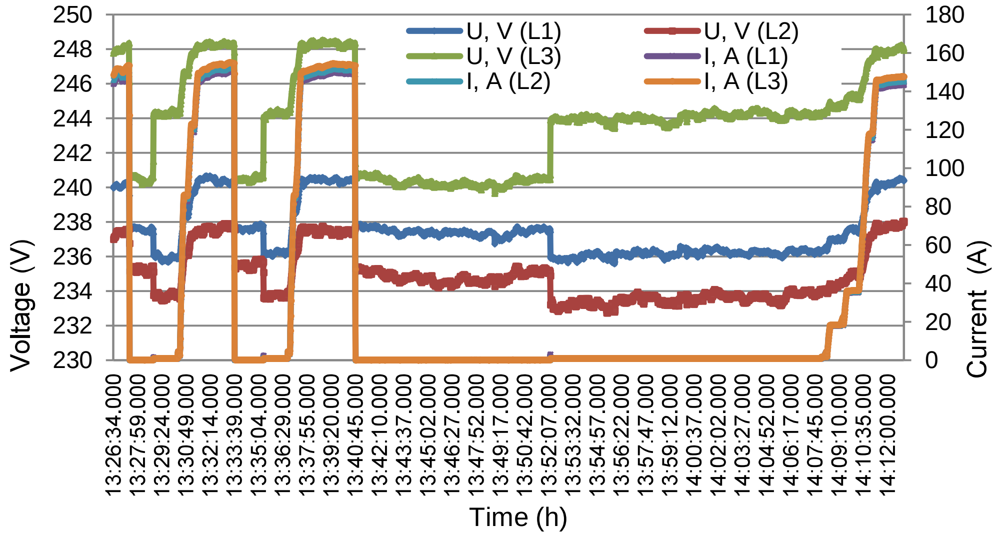

Figure 13. Network voltage and current exiting the station during attempts to disconnect the entire station.

The solar power plant was kept isolated from the grid for a longer period of time and also in idle mode to monitor both modes for extended periods. As a result of these experiments, it became clear that the inverters used in the power plant increase the phase-to-phase voltage difference in the low-voltage grid of the supplying substation. As shown in Fig. 13, when the power plant is switched on the voltages in phases L1 and L2 decrease by about 2 V and in phase L3 increase by about 4 V. As a result, the voltages of the phases L2 and L3 are 10 V instead of the previous 4…6 V.

At 13:28 and 13:35 the graph in Fig 13indicates that after the solar power plant is turned on, the inverters take about 2 minutes to reach full power. While productivity has increased sharply in the first two cases, productivity has increased gradually after being in idle mode. First, the 20 kVA inverters were turned on and then the remaining four 30 kVA inverters.

Fig. 14 shows the total harmonic distortion in the low-voltage grid of the supplying substation recorded during the station shutdown tests. The graph shows that the level of harmonic distortion is lowest when the solar power plant is isolated from the grid. The distortion is then up to 1%. At the time when the solar power plant inverters are turned on in idle mode, the harmonic distortion in the two phases increases by about 0.2%. The figure also shows that as the output of a solar power plant begins to increase, the proportion of total harmonic distortion of the voltage increases to 1.5%.

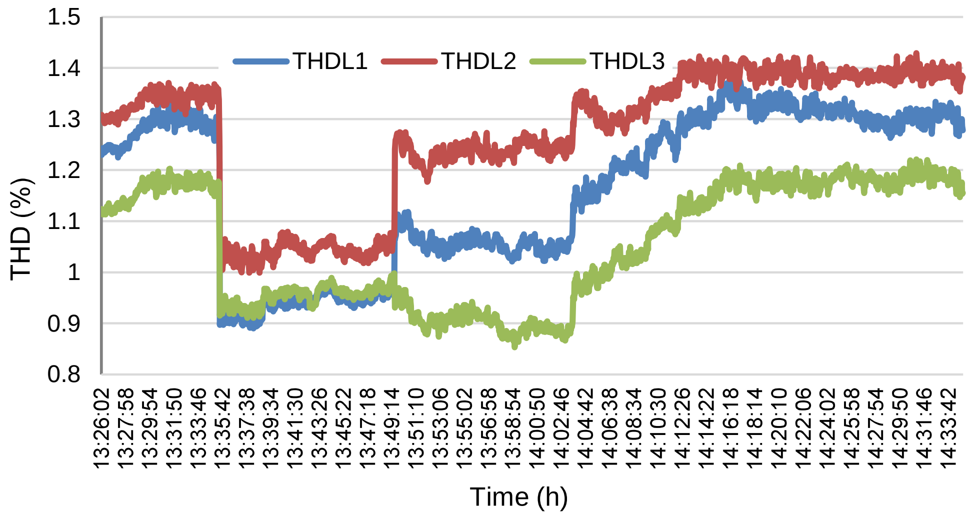

Figure 14. THD of three-phase voltages during disconnection attempts.

Fig. 15 shows the third harmonic level of the low voltage network. Phase L2 levels are approximately 2-fold greater than those of phases L1 and L3. The graph shows that the third harmonic level is independent of the productivity of the solar power plant. The harmonic level rises sharply the moment the inverters are connected to the mains in idle mode and then remains stable between 0.7% and 0.8%. The third harmonic limit stated in the relevant EN 50160 standard is 5%.

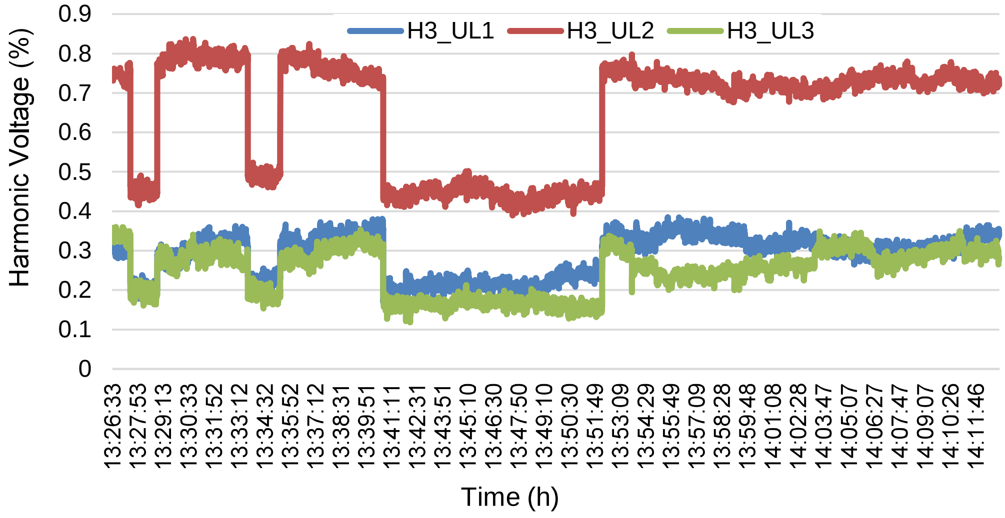

Figure 15. Voltage third harmonic levels during disconnection attempts.

Fig. 16 shows the 11th and 13th voltage harmonic levels of the low voltage network of supplying substation. Unlike the 3rd harmonic, the proportion of these harmonics will not increase until the solar power plant starts supplying electricity to the grid. The 11th harmonic levels are less than 0.9% and the 13th harmonic level below 0.4%. According to the standard EN 50160, the highest levels for the 11th and 13th harmonics are 3.5% and 3.0%, respectively. Similar is valid for the 17th and 19th voltage harmonics trends shown in Fig. 17. These harmonics are up to 0.4%, and the standard EN 50160 allows for 17th harmonics to be 2.0% and 19th harmonics to be 1.5%.

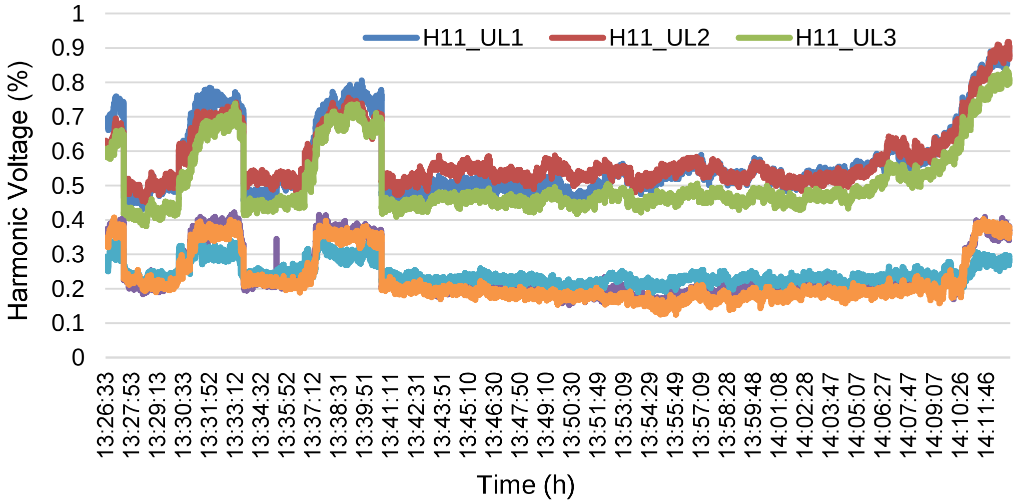

Figure 16. 11^{th} and 13^{th} voltage harmonics levels during disconnection attempts.

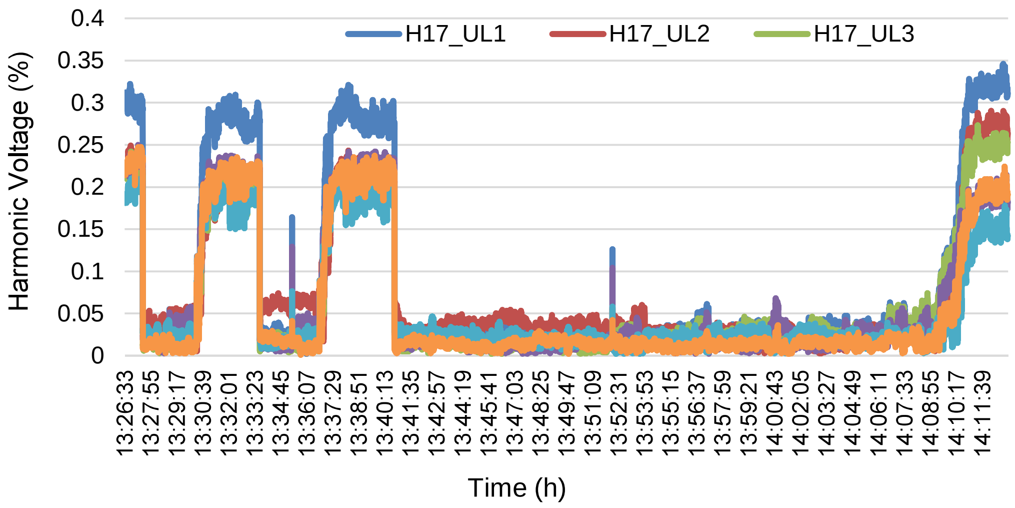

Figure 17. 17th and 19th Voltage harmonics during disconnection attempt.

CONCLUSIONS AND FUTURE WORK

As more and more PV microgeneration systems are installed to the LV grids, power quality issues in the LV networks have to be studied accordingly. While recently the number of studies addressing these problems has increased considerably impact of PV systems upon voltage quality in weak rural LV networks remains unclear.

Results in this paper reflect a 160 kW solar power plant and its impact on the LV network, with the daily average output power for the first week of measurements of is 56 kW, for the second week is 47 kW and for the third week is 50 kW. On average, the phase voltages increased from 236 V to 242 V when the power of the station was close to the maximum. Phase voltages fluctuated between 230 V and 246 V during the three weeks' time. In addition to the voltage increase, as the output power increases the solar power plant has an effect on the rapid change in voltage. The rapid change in power can be caused by clouds.

The measurement records included also the maximum and minimum voltages for one minute. The difference between these values was often up to 8 V over three weeks. Due to the clouds, the output power drop by 130 kW was recorded, resulting in a voltage drop of about 7 V. It is also clear from the figures that at night the mains voltage is more stable than during the day. The standard requires consumers to have a voltage within ± 10% of the rated voltage, or between 207 V and 253 V. As the voltage at the consumer, point depends on the parameters of the lines connecting to the substation, the available data from the substation does not allow an assessment of whether the consumer's supply voltage is above 207 V.

The positive impact of the PV power plant on the low voltage grid is manifested in reducing the voltage asymmetry by increasing the output power. The average reduction in asymmetry at 160 kW output power is from 0.50% to 0.35%, or 0.15%. Voltage asymmetry up to 1% is considered a high-quality indicator, however solar power plant still provides a reduction to it.

The measurements were expected to provide an insight into the effect of solar power inverters on the total harmonic distortion of a voltage. Measurements revealed the smallest voltage total harmonic distortion at the moment when the solar power plant is completely disconnected from the grid. The distortion increased by about 0.2% when the inverters were connected to the grid in idle mode, and when the power was supplied to the grid, the proportion of total harmonic distortion increased further by about 0.3%. This means that due to the solar power plant, the total harmonic distortion in the grid would increase by 0.5%. Since only a few cases had a total harmonic distortion of more than 2% over a 3-week period, these solar power inverters are rather unlikely to cause the permitted values to be exceeded in this particular grid.

The analysis was carried out for both sunny, cloudy and alternating cloudy days. As the measurements were conducted in September, when the intensity of the sun is not at peak, some more measurements in the middle of summer with the highest intensity of the sun and longest daytime are feasible. Measurements should also be carried out on this low-voltage grid in the winter when the solar power plant is in standby rather than in operation for most of the time. These additional measurements would allow a more accurate assessment of the effect of this solar power plant on the low voltage grid.

In addition, tests could be conducted on how a given PV plant will behave when the transformer is shut down. It is also unknown at this time how this solar plant will respond to short circuits in both low voltage and high voltage networks. Attempts to answer these questions would require prior coordination with consumers, as power outages may occur.

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